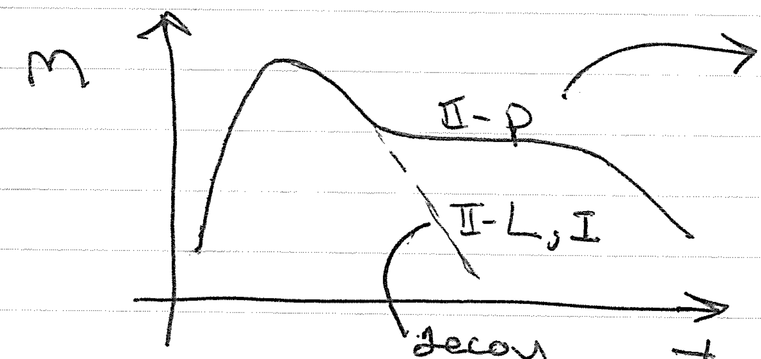
Supernovae

Classification

Type I (no-H) Type II (H)

Type I (no-H)		Type II (H)	
Ia	Si II line @ 615 nm	II	P/L/N
Ib	He I line @ 587 nm	IIb	changes to Ib
Ic	no He, H or Si		



~~M~~ H-recombination wave

$M \simeq \frac{L t^3}{q(t_b)\, t_b}$

$t_p \simeq 100$ day

^{56}Ni 6d ^{56}Co 77d ^{57}Co 272d ^{44}Ti 60y

$L_{bol} \simeq 1.64 \cdot 10^{42}$ erg/s

Ia are thermonuclear supernovae

The rest are powered by gravity as the collapse of a massive star's ~~Fe~~ core

8-10 $M_\odot$	electron capture O/Ne/Mg	II-P	faint
10-25 $M_\odot$	iron core	II-P	faint
25-40	iron core	II-P	normal
high Z		II-L, IIb	
$\gtrsim 40$	iron core	Ibc (GRB?)	

The iron core:

$$M_{ch0} = 5.83 Y_e^2$$

Y_e ranges from 0.42 to 0.48

so $M_{ch0} = 1.18 M_\odot$

However, the core is hot, consists of charged particles and surrounded by matter.

Before considering entropy $M_{ch0} = 1.15 M_\odot$

$$M_{ch} \approx M_{ch0}\left[1 + \left(\frac{s_e}{\pi Y_e}\right)^2\right]$$

$$s_e = \frac{S_e}{N_A k} = \frac{\pi^2 T Y_e}{\epsilon_F} \simeq 0.50\, \rho_{10}^{-1/3} \left(\frac{Y_e}{0.42}\right)^{2/3} T_{MeV}$$

In the core of the $15 M_\odot$ star, s_e ranges from 0.4 - 1, so $M_{ch} \approx 1.34 M_\odot$

*) As long as there is burning in the core, it won't collapse.

The core grows through a series of Si burning shell flashes, the last will overshoot M_{ch}

Once the core exceeds M_{ch} it will collapse but neutrinos must carry away the binding energy

↳ thermal timescale

As $\rho\uparrow$ e^- capture onto nuclei reducing Y_e and the pressure

$p \propto T_e^3$ so the matter heats up.

Nuclei photodisintegrate increasing # of α particles absorbing energy and reducing S_e

Furthermore, energy excites the nuclei (many exponentially states)

So heavy nuclei persist and collapse continues until nuclei touch

ρ increases to a few ρ_{nuc} and nucleons start to repel each other.

Core of star collapses homologously var; it is also in sonic communication

After bounce shock forms at edge of homologous core

- The shock propagates outward but loses 10^{51} erg per $0.1 M_\odot$

so it fails ☹

- 10 ms after core bounce have protoneutron star with $\dot{M} = 1-10 M_\odot s^{-1}$

- The neutron star has a binding energy finally of

$$\Omega = \frac{3}{5-1} \frac{GM^2}{R} \qquad (n=1 \text{ polytrope})$$

$$\Omega = \frac{3}{4} \frac{GM^2}{R} \approx 4 \cdot 10^{53} \text{ erg} \left(\frac{M}{1.4 M_\odot}\right)^2 \left(\frac{R}{10 \text{ km}}\right)^{-1}$$

- As a protoneutron star $R \approx 100$ km

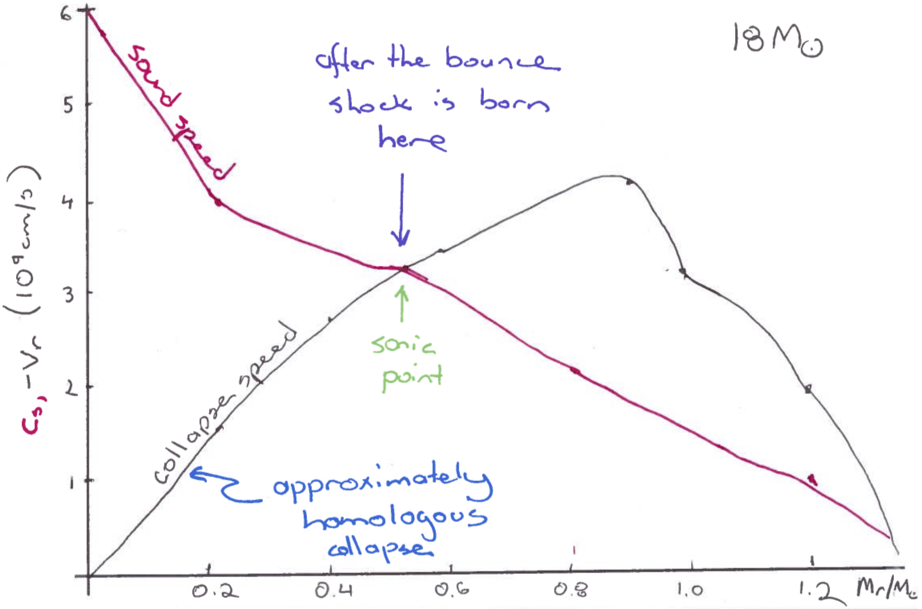
- This energy is now in the form of the heat of the NS

- It is released on a thermal timescale of 3-10 s through neutrinos

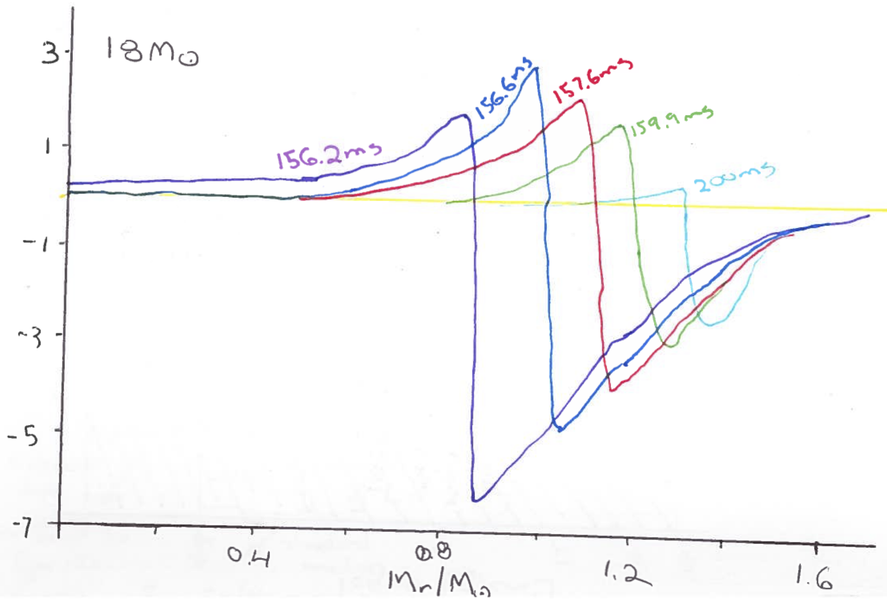
- Only ~10^{51} erg is required to unbind the rest of the star.

- Neutrinos deposit energy in the failed shock and revive it

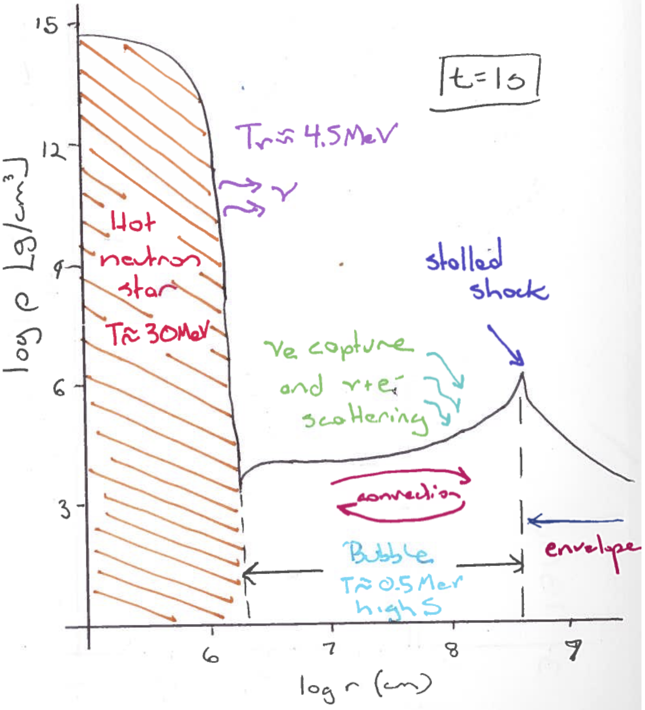
(convective, shearing ...)



18M☉
sound speed
after the bounce shock is born here
sonic point
collapse speed
approximately homologous collapse
$c_s, -v_r$ (10^9cm/s)
6
5
4
3
2
1
0.2
0.4
0.6
0.8
1.0
1.2
$M_r/M_☉$



18M☉
156.2ms
156.6ms
157.6ms
159.9ms
200ms
3
1
-1
-3
-5
-7
0.4
0.8
1.2
1.6
$M_r/M_☉$



t=1s
15
12
9
6
3
log ρ [g/cm³]
Hot neutron star
T≈30MeV
Tν≈4.5MeV
ν
stalled shock
νe capture and ν+e⁻ scattering
convection
Bubble
T≈0.5MeV
high S
envelope
6
7
8
9
log r (cm)

Thermonuclear supernovae

- C/O white dwarf near $M_{ch} \approx 1.4 M_\odot$
- or C/O white dwarf with He mantle, below M_{ch}
- no hydrogen, no radio emission
- powered by decay of ^{56}Ni
- But WD are typically about $0.6 M_\odot$ so must grow through accretion or merger (emission of GW)

- Single Degenerate scenario
  - At low $\dot{M}$, H-burning is unstable
    ↳ novae and $M_\star \downarrow$
  - At high $\dot{M}$, WD becomes a red giant and H-burning is stable but then Type II
  - Observed accreting WDs do not have $\dot{M}$ for stable H-burning

But "Supersoft X-ray Sources" maybe do

The uniformity (one parameter deviations) point toward the single degenerate model.

- For example the C/O in the center of the WD will affect the total energy released and depend on the mass of the progenitor of the WD.

- The core thermal budget:

  $\nu_{plasmon} \leftrightarrow$ compressional heating

- but as $\rho \uparrow$ $\nu_{plasmon} \downarrow$ quickly

  so above $2 \cdot 10^9$ g cm^{-3} plasmon neutrinos are not important

  But electron screening of reactions is so nuclear runaway begins.

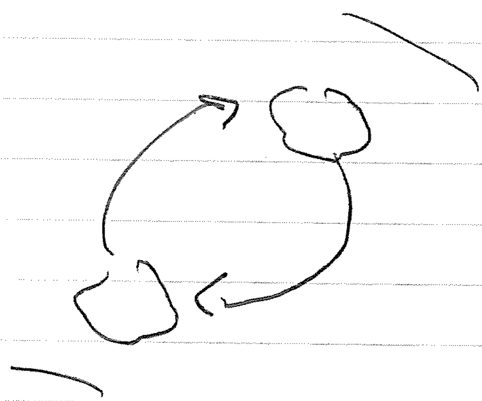
  Over ~1000 yr $\tau_{convection} \downarrow$; $\tau_{burn} \downarrow$

- New ν production convective Urca

  $$\frac{\partial \log L_\nu}{\partial \log T_c} \approx 170 \text{ !!}$$ (Paczyński '72)

- $e^- + (Z,A) \rightarrow (Z-1,A) + \nu$ at high ρ

  $\cancel{(Z-1)}\ (Z-1,A) \rightarrow (Z,A) + e^- + \bar{\nu}$ at low ρ



- Because the ☆ is convective at the core we have this process which slows convection

At $T \approx 7 \cdot 10^8$ K τ_c and τ_b become comparable so convective burning

At $T \approx 1.5 \cdot 10^9$ K $\tau_c \ll \tau_b$ so C+O burning in place and electron conduction carries heat

↳ ignition of nuclear flame ($l \approx 10^{-4}$ cm)

- At this point the core isn't sufficiently uniform for a detonation front to form and go thru the ☆

- The flame grows and brings in more fuel thru the induced turbulent motions
- Could form a detonation front

C/O or Ne/O/Mg White Dwarf